TREATMENT AND MAINTENANCE OF STORMWATER HYDRODYNAMIC SEPARATORS: A CASE STUDY

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ABSTRACT

A commonly utilized BMP in MS4s and new construction is a screened hydrodynamic separator. These devices are intended to separate gross solids and associated pollutants without providing hydrologic restoration. This case study examines the performance of a common screened (2400 μm screen) hydrodynamic separator with and without maintenance (cleaning). The design of experiments was based on utilizing flow rates ranges from less than 10% to 125% of manufacturer design flow and followed regulatory protocols (Indianapolis). Results were also modeled through computational fluid dynamic (CFD) modeling. Results indicate that for the class of hydrodynamic separators examined, that while gross solids can be removed, regular maintenance or cleaning is critical to maintain effluent quality. The case study illustrates, from measured and modeled data that lack of maintenance can lead to significant scour (and partitioning) of existing loads from a screened hydrodynamic separator. Results suggest that structural BMP systems must include hydrologic restoration, frequent maintenance, sludge/solute management and should be considered only after source control measures have been shown not to be effective in an MS4.

INTRODUCTION

Gross pollutants are often the first type of stormwater pollutants targeted in urban catchment management for water quality improvement. A hydrodynamic separator (HS) can be effective in the removal of gross solids and debris (Wong et al. 1995) with a mean removal efficiency of approximately 60% for gross solids (Walker et al. 1999). This degree of success has encouraged a widespread implementation of HS systems in stormwater (Schwarz and Wells 1999), combined sewer overflows (Heist et al. 2003), parking lot runoff treatment, and oil and grease removal (Stenstrom and Lau 1998) to try and mitigate negative impacts of stormwater. However, as it would be expected, treatment performance depends on many factors. One factor is how well the BMP is maintained in relation to the original design condition of the BMP. For example, one design component of a HS is the unit volume and the separation of the sludge level from hydrodynamic flow through the HS. This separation is progressively reduced over time as more sludge is collected. The rate of accumulation and the corresponding loss of treatment volume largely depend on the amount of particulate matter that enter the unit, and are captured and the sizing of the HS. Thus higher solids separation effectiveness tends to yield faster accumulation within the unit.

This study was prompted to examine the effect of increased solids accumulation on the degree of resuspension and the scouring of preloaded sediments due to influent flow hydraulics. These trapped sediments may be scoured, re-suspended and discharged through effluent flow, resulting in higher pollutant effluent concentrations than that in event-based treatment tests where scouring effects are not taken into consideration. Therefore, frequent sludge removal is a key component of maintenance to ensure that the HS continue to operate as intended.

Another important aspect of the proper maintenance is that many stormwater BMPs detain runoff for extended dry periods of time (hours to days) between events which often creates anoxic/anaerobic conditions within a treatment system. Such changes of water chemistry during the detention time may alter partitioning and speciation of metals and nutrients significantly (Nelson et al., 2006). It implies that pollutants once considered "trapped in a BMP" could be released back into aqueous phase which can be flushed by subsequent storm event. The presented study has evaluated resuspension (scour) of accumulated sediments quantitatively in a HS. As a separate subject, this paper also presents the time-dependent changes of pH and redox potential within a volumetric treatment unit which contains pre-deposited particulate matter from 11 consecutive previous storm events generated from an urban source area watershed.

In recent years, Computational Fluid Dynamics (CFD) has been increasingly utilized to model flow/particulate behavior in BMPs. Various models have been developed for dilute multiphase flows, based on concepts of computational fluid dynamics (CFD). Multiphase CFD models have been used in modeling hydrodynamic separators. In previous research the applicability of CFD in modeling combined with the required calibration/validation for particle separation behavior of a HS has been demonstrated by the authors. A finite volume method (FVM) approach was used to model the particle separation behavior of a HS. Results indicate that the model predictions of effluent concentrations reproduce the measured data with the absolute relative percent difference (RPD) between measured and modeled results less than 10 percent.

Re-suspension of particles was studied using a user-defined function at the boundary, i.e., the sludge level in the sump and volute section of the screened HS. Empirical formulae are typically obtained for bed shear stress for specific solids. This approach defined a critical bed shear stress above which a particle would be re-entrained. The flow regime in a HS is turbulent, complex and predominantly vortex driven. This implies the challenge of measuring/utilizing bed shear stress as a parameter by which scour is defined. To model local scour is a very computationally and numerically extensive process, especially in three dimensions. Many techniques that use moving meshes to model local scour have been proposed, and most of these are in nascent stages of development predominantly used in 2D models. The study herein utilizes Computational Fluid Dynamics (CFD) with a modified particle tracking approach to model scour of pre-deposited sediment in a hydrodynamic separator.

METHODOLOGY

Site set up and configuration

The testing facility employed for this evaluation was located under the I-10 bridge overpass at City Park Lake and East Lakeshore Drive in Baton Rouge, Louisiana. A screened hydrodynamic separator (HS) was installed on the concrete slab of the testing facility. The HS with 84 inch (7 ft) diameter has a 25 ½-inch diameter screen eccentrically located with respect to the center of the unit. Details of the site configuration, setup and dimensions are illustrated in Figure 2. This standard unit is typically a 60 inch diameter, but 72 and 84 inch diameter units were also tested to demonstrate improved performance with larger unit diameters and examine the role of scaling. In order to try and achieve an 80% removal efficiency for the greatest fraction of the stated design flow rate and based on SSC, while also minimizing scour, the largest unit, an 84 inch unit is examined herein, The flow monitoring system consisted of a 6-inch Parshall flume, 100 kHz ultrasonic sensor and flow appurtenances. The flow monitoring system was calibrated over the full range of flow rates; from a minimum flow rate of 51.7 gpm to a maximum flow rate of 640.7 gpm. A diesel pump with a capacity of 1100 gpm and the recirculation system were used to reach throughout the range of flow-rates tested in this study. Potable water was stored in the 10,000 gallon influent baker tank and used for influent flow.

Particle size distribution for both treatment and scour tests

Influent particles for treatment tests and the pre-deposited solids used in a series of the scour tests are composed of a significant fraction of sand size particles over a narrow range of particle size; 94.6% of the mass occurs within the size range of 75 to 150 μm with a d_{50m} of 112 μm. Based on Unified Soil Classification System (USCS); this gradation is classified as poorly graded sand and noted as SP (ASTM 2006). Particle size distribution of SP is described in Figure 2 and consistently used as pre-deposited solids for scour testing.

Treatment performance tests (without scour)

The treatment performance (without scour) of the HS with a 2400 μm screen was tested at constant flows from approximately 10 to 100 % of design flow rate (494 gpm) in 10% increments. Influent particle loading conditions include a nominal influent concentration of 200 mg/L (± 4.2 mg/L) and SP particles (d_{50m} = 112 μm). This gradation is illustrated in Figure 2. Since scour and consequent maintenance is the primary focus of this study, the clean-unit treatment performance will be summarized, but is not a major focus since a screened HS is generally does not perform under clean-unit conditions in the field.

Prior to starting each test, tanks, the HS, and the entire flow transport system were thoroughly cleaned using potable water to ensure that there are no pre-deposited particles or external solid materials in the entire components of system. When the flow reached steady state, at the chosen flow rate, the test was started. The influent particles (SP) with a consistent size distribution were injected into the drop box located downstream of the Parshall flume. The rate of particle injection was consistent across the period of each treatment run, on a gravimetric and granulometric basis. 20 individual replicate (A and B) 2 L effluent samples were collected for SSC analyses at consistent sampling intervals throughout the duration of test which was calculated based on flow rate being tested. Overall influent treated volume was around 28,000 L per each run. This represents approximately 10 effective volume of the HS with an 84 inch diameter. Replicated effluent samples were also collected and transported to the laboratory. SSC analysis was done by filtering the entire volume (~90-L) of replicate samples captured through a nominal 1 μm fiberglass filter (ASTM, 1999).

Scour tests

The potential for re-suspension and washout of solids (as SP) in the HS was examined with three sets of experimental parameters:

1. flow rates (100% or 125% of the design flow rates, 494 gpm),
2. preload in the sump (50% or 100% of sump depth),
3. preload in the annular (volute) area (0 or 1 inch depth).

The standard sump provided by the manufacturer was a cylindrical section attached under the bottom of the HS with the dimension of a 25 inch diameter and an 18 inch depth (Volume ≈ 150 L). This configuration is illustrated in Figure 1. The sump was pre-filled with SP solids to either 50% or 100% of the sump depth. At each preload setting in the sump, the volute section (32443 cm^2) was filled with either 0 or 1 inch depth of the solids. Once the HS was pre-filled with sediment, the HS was then filled with potable water (~2814 L) at a low flow rate, chosen to minimize any re-suspension prior to starting the actual test. An additional 20 minutes of quiescent settling time was allowed to ensure that there was no solids suspended in the sump and volute areas at the start of each test. For effluent sampling a total of 20 4 L individual samples were taken in duplicate, at a consistent sampling interval calculated based on flow rate being tested. The total influent volume (27,500 L) was constant for each run. 5 replicate composite effluent samples were consecutively prepared throughout the test duration. Each composite sample contains 4 individual replicate (A or B) samples. Suspended sediment concentration (SSC) was measured for each composite sample. SSC analysis was carried out by filtering the entire volume (~90 L) of replicate composite samples through a nominal 1 μm fiberglass filter (ASTM, 1999). The results expressed the intensity of scouring as scouring rate (g/min) while the magnitude of scour was evaluated by effluent mass load. All influent was clean potable water with no solids.

Computational Fluid Dynamics Model

The laws of conservation of mass and momentum are the foundations of CFD. The generalized three-dimensional scalar conservation equation for a control volume with volume $V(=\partial x \partial y \partial z)$ is given in the following equation.

$$\frac{\partial(\rho\Phi)}{\partial t} + div(\rho\Phi\bar{u}) = div(\Gamma grad\Phi) + S_\Phi \qquad (1)$$

In this expression, Φ is any fluid property per unit mass, such as mass fraction, velocity, etc; $\bar{u}$ is the fluid velocity, [LT^{-1}], Γ is the diffusion coefficient, [L^2T^{-1}]; S_Φ is the source/sink term. The mass continuity equation is obtained by assigning a value of 1 to Φ. The momentum equations for the x, y and z directions respectively can be obtained by assigning values of u, v and w correspondingly, where u, v and w are the x, y and z vector components of fluid velocity respectively.

Modeling fluid flow in the HS

Turbulence dominates the flow regime inside the HS. Turbulent flow models were based on a turbulence approach and were obtained by the Navier-Stokes equations. A standardized turbulence model was utilized in this study to resolve turbulent flow.

The screen in the HS was measured and then modeled geometrically as an addition component source term to the standard fluid flow equations. The previous study reported that the pore area open to flow is approximately 20% of the total plate area in the direction perpendicular to the plate and 40% when viewed against the direction of flow (Wong 1997).

Modeling the particulate phase

Due to the turbulence of flow and suspension of particles, a particle tracking approach was chosen to model particle separation. In this approach, the flow field was first resolved. Following this, particles were tracked. The particle tracking was derived from force balances based on classical turbulence and transitional flow regimes and consideration of laminar flow regime mechanics.

Particle trajectories were obtained through integration of the resulting equations of motion. Particles were tracked for a specific length for each flow rate, based on hydraulic residence times and those that remained in the HS after being tracked over the specified length were considered to have been separated by the HS. Particle removal was defined by the following equation.

$$\Delta p = \frac{N_{HS}}{N_I} * 100 \qquad (2)$$

In this expression, N_{HS} is the number of particles that remain in the HS, and N_I is the number of particles injected at the inlet.

Discretization and solution schemes

A three-dimensional (3-D) modeling approach was used in lieu of a simpler 2-D approach to account for the complexity of the HS geometry. Progressively finer meshes were tested and mesh refinement beyond 2 million computational cells had no significant effect model performance, confirming that the solution is grid independent. Algorithms were chosen to account for pressure-velocity coupling.

Time-dependent water chemistry in a stormwater BMP

Water chemistry parameter including pH and redox potential were monitored to demonstrate the dynamics of water chemistry within a separate treatment unit on site during dry period between actual storm events. To examine the changes in water chemistry in a stormwater BMP, 12 actual storm events were captured at the site, allowing sludge to accumulate, and the initial time t_0 in this study started at the end of the last event. After the end of runoff the unit was left with an un-drained volume typical of runoff volume retained in most below grade BMPs. After the end of the last runoff event the unit was isolated from the catchment drainage to simulate a dry period for this study. This study was carried out separately from the scour and treatment testing. Samples were taken at 0 h, 0.5 h, 1 h, 6 h at the end of runoff and 12 hour interval after the event for eight days. Water quality including pH and redox potential were recorded 1 hour interval. All samples were replicated and preserved according to the standard methods prior to the analysis. Dissolved fractions were separated using 0.45 μm membrane filter immediately after collection. Water chemistry included N and P species as well as particle size distributions.

RESULTS AND DISCUSSION

Treatment performance tests

Ten treatment performance tests were conducted at constant flows from 10 to 100 % of design flow rate (494 gpm) at a nominal influent concentration of 200 mg/L (± 4.2 mg/L) with SP particles. Note that each treatment test was performed under no pre-deposited condition. Given the HS configuration and loading conditions (influent concentration and PSD), the separation efficiency of the 84 inch diameter screened HS with a 2400 μm screen ranged from slightly greater than 90% to 60 %, for flow rates tested that ranged from 49.4 to 494 gpm (10 to 100 % of design flow rate), based on suspended sediment concentration (SSC). The arithmetic mean separation efficiency performance of the HS was approximately 82% for the 84 inch diameter configuration if all flow rates from 10 to 100% are weighted equally. It was observed that particle separation behavior of the screen area and volute area, for this configuration and loading condition are inversely related as a function of design flow rate; up to approximately 60% of design flow rate.

Scouring tests

The potential for re-suspension and washout of preloaded sediments with a specified gradation in HS was examined with three experimental parameters; flow rates (100% or 125% of the design flow rates), preload in sump (50% or 100%) and in volute (0 or 1-inch depth). Figure 3 illustrates the loading conditions and Table 1 summarizes the results of eight scouring runs performed for the HS with solids (SP gradation) pre-loading. For the 100 % pre-loaded sediment level in the sump, results from the scouring runs indicate that with a SSC influent level of approximately 0 (clean potable water) and two different flow rates (100% and 125% of 494 gpm) effluent particle concentration was in the range of 175 to 197 mg/L. However, when the preloaded sediment level in the sump was reduced to 50% of sump capacity, the souring run resulted in an effluent SSC level from 103 to 117 mg/L which is approximately 40% lower than with full pre-loaded sediment in the sump. When volute area were also pre-loaded with 1 inch of SP (100% sediment load in sump), there was not a significant increase in effluent SSC which ranged from 180 to 200 mg/L, compared to no sediment load in volute area. For pre-loaded condition on both sections (50% in the screen area and 1 inch of SP in volute section), effluent SSC was 107 to 116 mg/L for 100% and 125% of design flow rates respectively.

As depicted in Figure 4, scouring tests of the HS with a 2400 μm screen indicate that the preloaded sediment height in the sump had the most dominant impact on the degree of scour during the duration of each run. Flow rate also make a significant difference on effluent particle concentration. Results demonstrate the significant impact of preloaded sediment on the quality of effluent flow, suggesting the management of clean-out schedules and procedures are required for successful performance. Sump and unit re-design are critical factors to ensure that captured materials are not scoured from the system.

Modeling scour of pre-deposited sediment in hydrodynamic separators

Model results are presented in Figure 5. Absolute relative percent difference (RPD) was chosen as a parameter to compare the measured data with the modeled data. Figure 5 compares effluent mass loadings of measured and modeled data, for an influent concentration of 0 mg/L, with the sump of the screened HS pre-loaded with sediment to 50 and 100 % of its capacity, at a flow rate of 590.7 gpm (38 L/s), which is approximately 125 % of the design flow rate. Results indicate that the model predictions of effluent concentrations reproduce the measured data. The absolute RPD was found to be less than 10 percent.

Figure 6 depicts fluid path lines inside the HS, for the design flow rate. These are the path lines of neutrally buoyant fluid "particles" in the computational domain. Median sizes for suspended (1 – 25 μm), settleable (25 – 75 μm) and sediment (> 75 μm) were selected from the real particles transported by urban runoff from a source area based on events captured at the testing site. Sizes chosen were 10.5 μm, 42.9 μm, 424.3 μm, respectively. For the pre-deposited conditions of three median sizes of particle fractions, scour and re-suspension in the HS at the constant influent design flow rate was modeled using CFD for each pre-deposited particle fraction. Figure 7 depicts scour and subsequent particle trajectories of a sediment sized particle (d_p=424.3 μm). It is immediately visible that for this particle diameter, re-suspension is not significant. On the contrary, Figures 8 and 9 depict significant scour for a representative particle in the settleable range (d_p = 42.9 μm) and a representative suspended particle (d_p=10.5 μm). It is immediately evident that these particles are scoured significantly by incoming flow, and are re-entrained, and eventually transported out of the HS.

Time-dependent changes of redox potential and pH in a stormwater BMP

As illustrated in Figure 10, after 15 hours of acclimation period where redox potential remains relatively constant in the runoff remaining in the unit, a rapid and significant decrease in the redox potential was observed through 48 hours of residence time. Concomitantly, consistent increase of ammonia concentration was identified while nitrate concentration exhibited opposite (decreasing) pattern as a function of residence time. Following initial 48 hours of resident time, decreasing pattern of redox potential was stabilized at a lower rate and redox reached a plateau of around -140 mV at 120 hours of residence time in the unit. For the balance of the 8 day monitoring period the redox remained at approximately -140 mV.

These redox results demonstrate that electrochemical condition inside of a BMP detaining runoff and particulate matter may be converted to an anoxic/anaerobic condition and acidic pH within a few days of detention time (48 hours in the present case study). This result is in agreement with the common understanding that rainfall-runoff collection system or treatment operation/process units where extended periods of residence time (hours to days) often occur undergo a transformation to anoxic/anaerobic conditions. The sludge trapped by BMPs contain a wide array of organic and inorganic pollutants such as metals, sulfur and nutrients (N, P). The presence of these constituents indicate that coupled changes in redox and pH due to progression down the redox ladder to anaerobic conditions causes significant alteration of mobility and species of N, P and metals. The potential mobilization of these pollutants from sludge to the water column in the BMP results in a “scour” or “first-flush” of these more mobile soluble pollutant species in addition to the scour illustrated for solids.

Results demonstrate that scour in a screened HS is significant and under periods of no flow (or low urban base flow) changes in water chemistry are also significant. With respect to operation and maintenance, stormwater BMPs illustrate similar mis-behavior as do wastewater treatment unit systems when these systems are not frequently managed. A wastewater plant would never operate a screened HS without frequent maintenance and cleaning or operate a primary clarifier without frequent sludge withdraw to prevent scour and upset to water chemistry. While the kinetics of these processes are different (a primary clarifier can go anoxic in several hours, while a stormwater BMP can go anoxic in several days) the resulting mis-behavior are the same without frequent maintenance and cleaning. Sludge pumps are generally operated on a 15 to 45 minute frequency in many wastewater clarifiers to ensure stable clarification and reduce sludge scour. By extension, frequent management is required for BMPs such as a screened HS or filter cartridge system to address misbehavior such as scour and re-partitioning. Ultimately, hydrologic restoration and pollutant source control is required given that this level of BMP management to ensure intended BMP performance is simply not sustainable.

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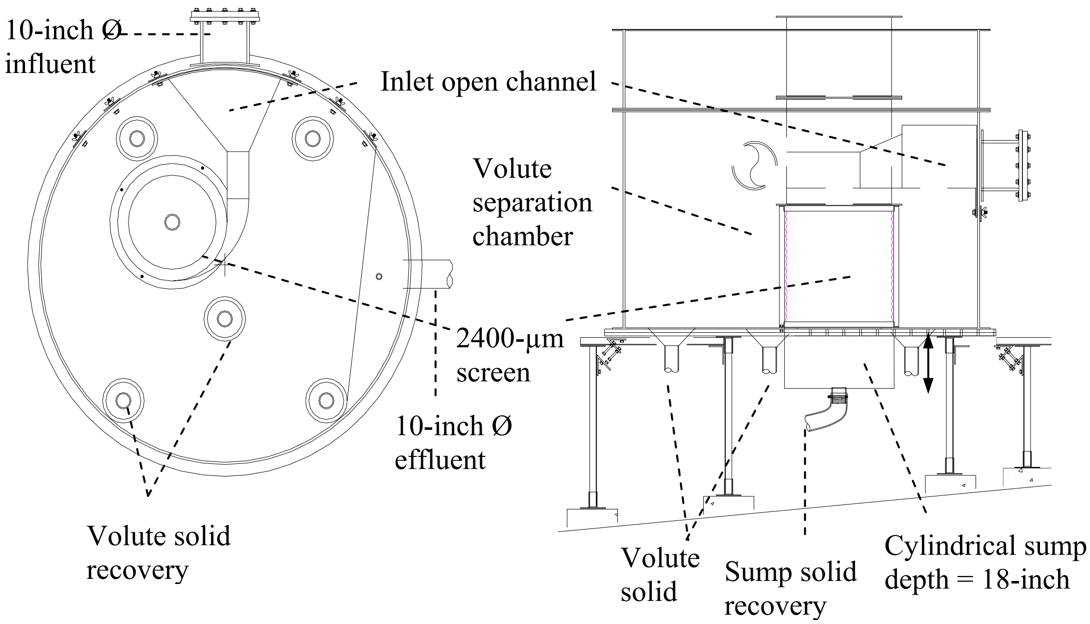


Figure 1. Diagrammatic cutaway and plan view of hydrodynamic separator and loading dimensions of the unit. The effective volume of the unit is the volume occupied by stagnant water without any influent flow. The standard screened HS is a 60 inch diameter, and the tested diameters were 60, 72 and 84 inches. Details of the 84 inch unit are examined herein.

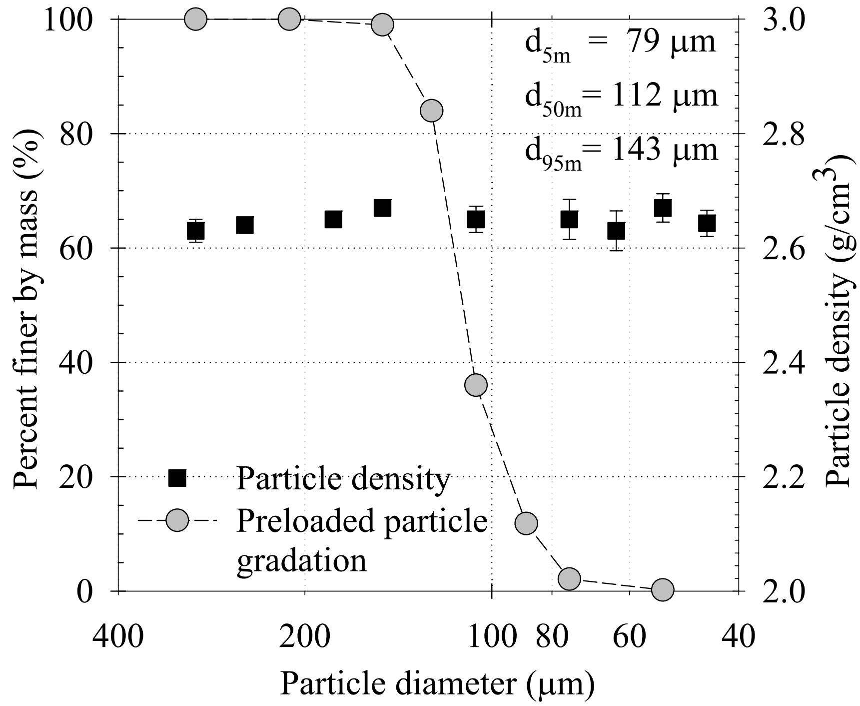
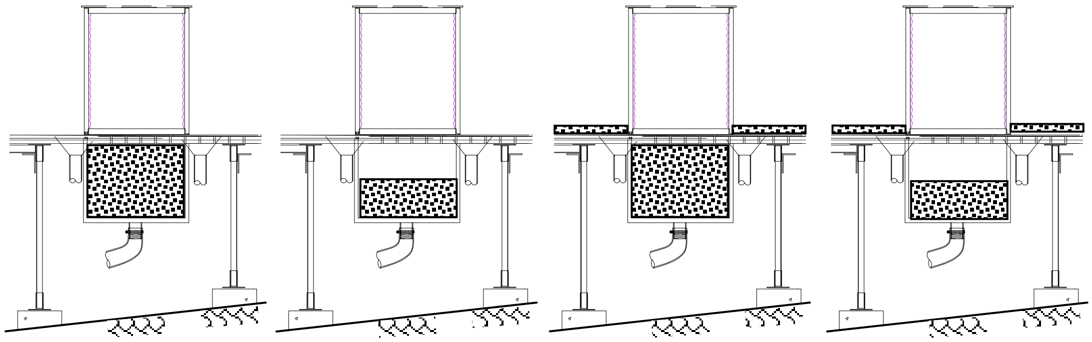


Figure 2. Particle size distribution classified as SP (poorly graded sand) used as preloaded solids in the HS for scouring tests. Particle density for all size of particles was measured as 2.65 g/cm^3 ± 0.05. The gradation is an US Silica OK-110 sand.



►**100%** particle preload in **Sump**
►**0 inch** particle preload in **Volute**
►**100%, 125% Q_{IN}**

►**50%** particle preload in **Sump**
►**0 inch** particle preload in **Volute**
►**100%, 125% Q_{IN}**

►**100%** particle preload in **Sump**
►**1 inch** particle preload in **Volute**
►**100%, 125% Q_{IN}**

►**50%** particle preload in **Sump**
►**1 inch** particle preload in **Volute**
►**100%, 125% Q_{IN}**

Figure 3. Initial sediment preloading conditions in the sump and volute area of tested HS and constant influent flow rates for scouring tests with SP gradation

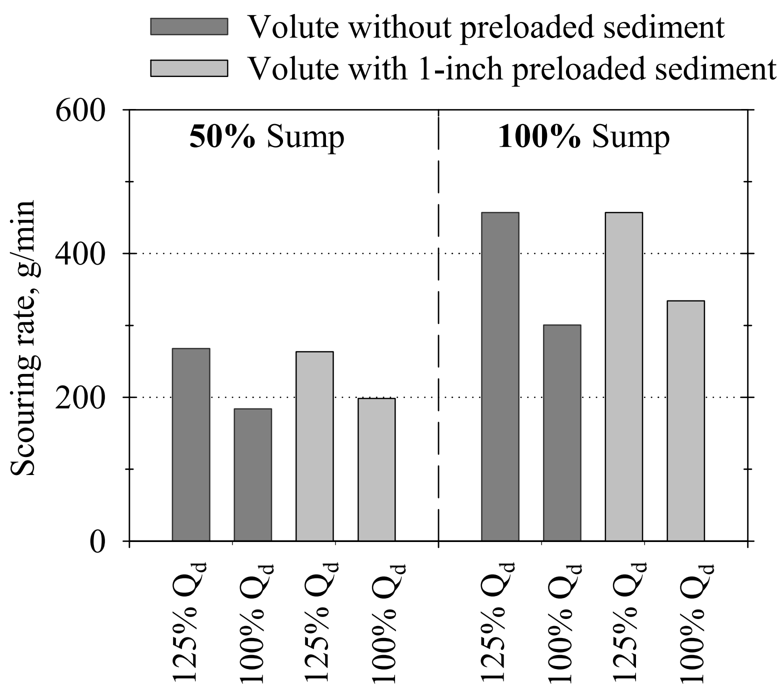


Figure 4. Sediment scouring rate from scouring runs with a 2400-μm in the 7-ft diameter HS Total influent volume (27,400-L) is set up as a constant parameter which determines duration of scouring run with target operating flow rates (100% and 125% of Qd). Qd: the design hydraulic operating rate for HS = 493.7-gpm.

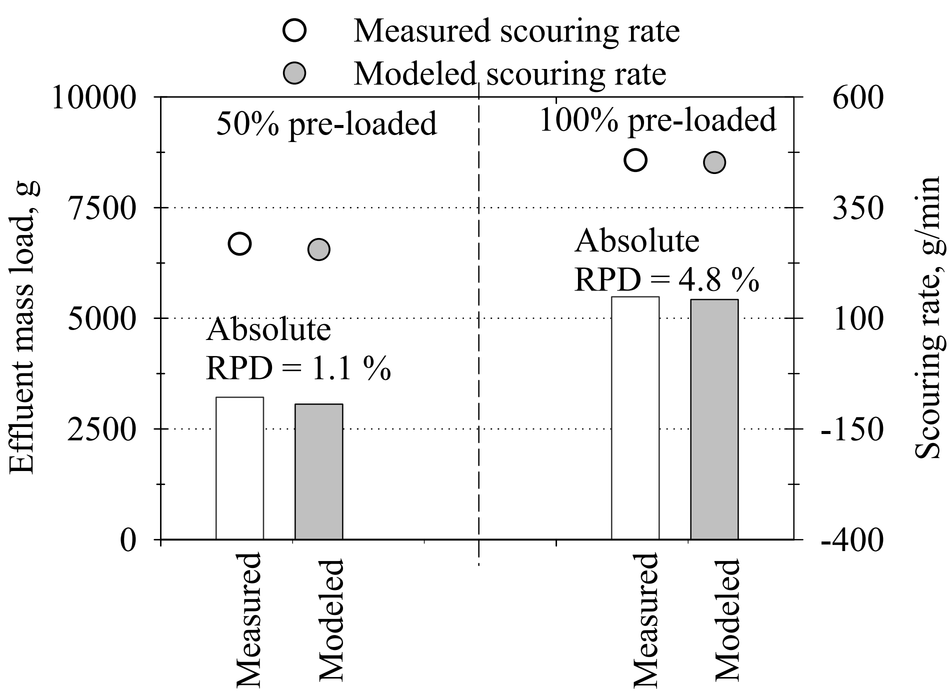


Figure 5. Measured vs. modeled effluent mass loads, and scouring rates for the screened HS with the sump pre-loaded with sediment to 50 % and 100% of capacity respectively.

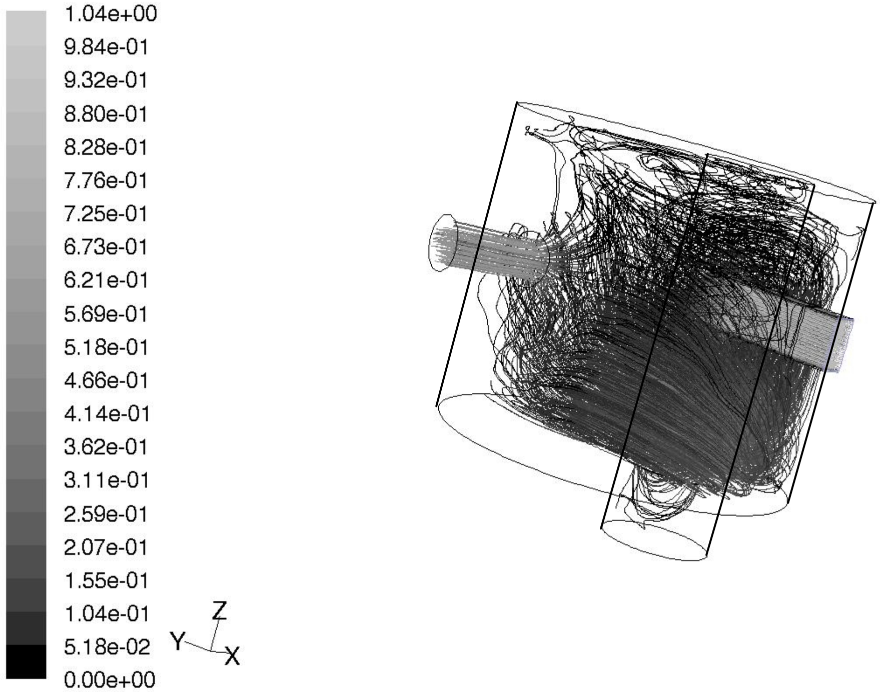


Figure 6. Fluid path lines in the screened HS for an influent flow rate of 590 gpm (38.1 L/s). Path lines are colored by velocity magnitude (m/s).

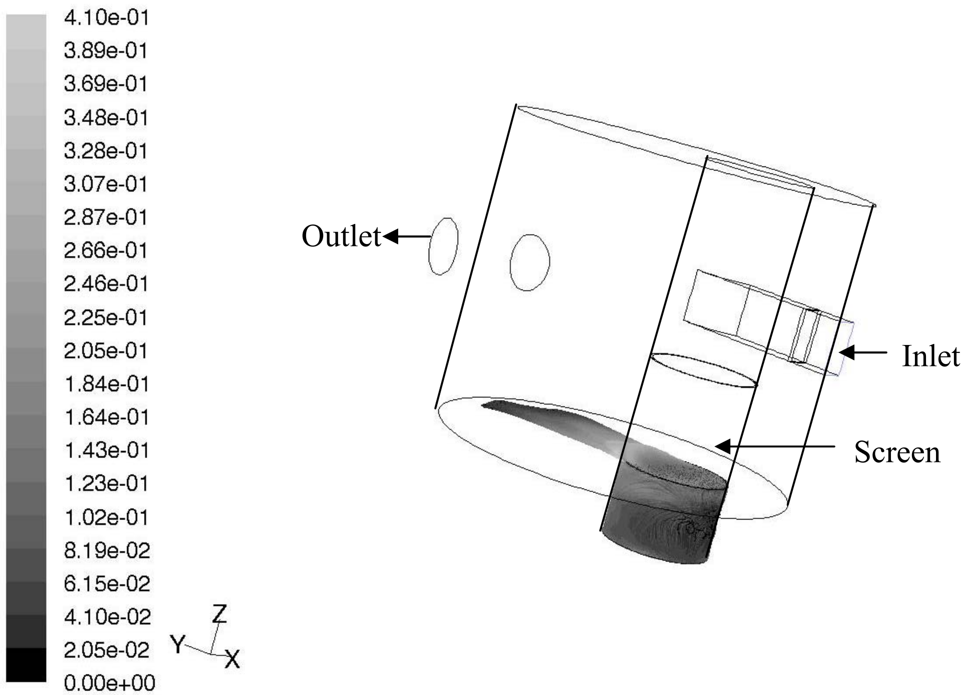


Figure 7. Scour of pre-deposited sediment size particles (median d_p=424.3 μm) at constant influent flow rate of 590 gpm for the HS with 2400 μm screen. Path lines are colored by velocity magnitude (m/s).

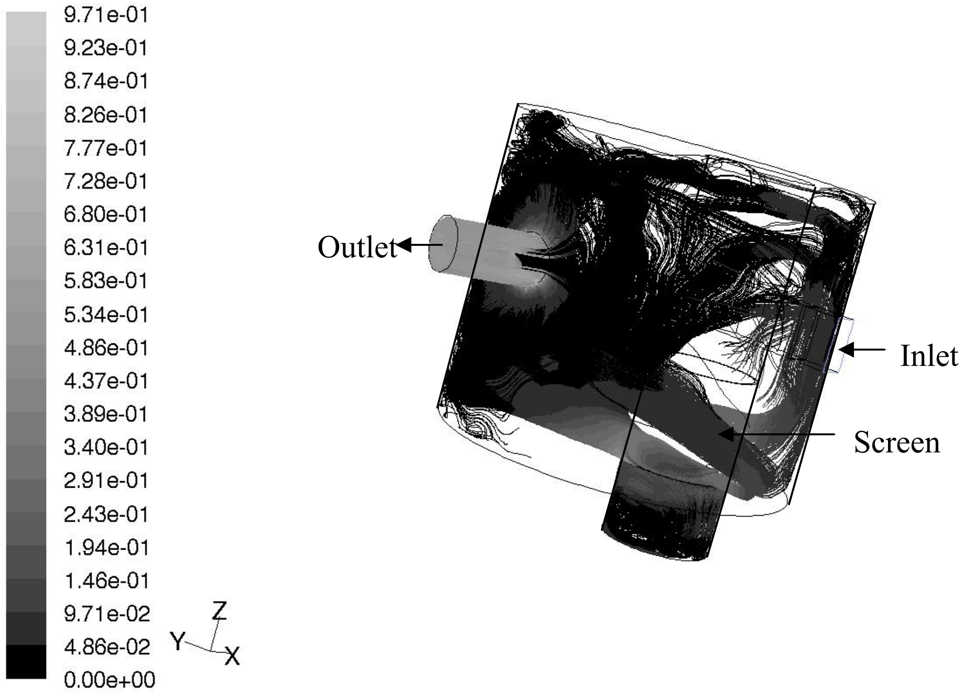


Figure 8. Scour of pre-deposited settleable size particles (median d_p=42.9 μm) at constant influent flow rate of 590 gpm for the HS with 2400 μm screen. Path lines are colored by velocity magnitude (m/s).

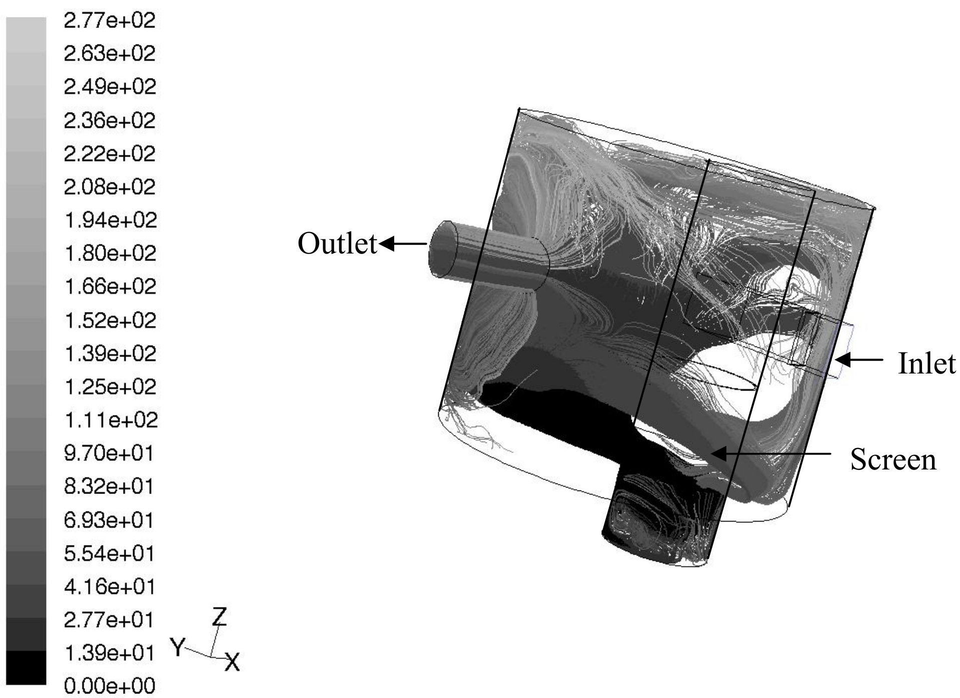


Figure 9. Scour of pre-deposited suspended size particles (median d_p=10.5 μm) at constant influent flow rate of 590 gpm for the HS with 2400 μm screen. Path lines are colored by velocity magnitude (m/s).

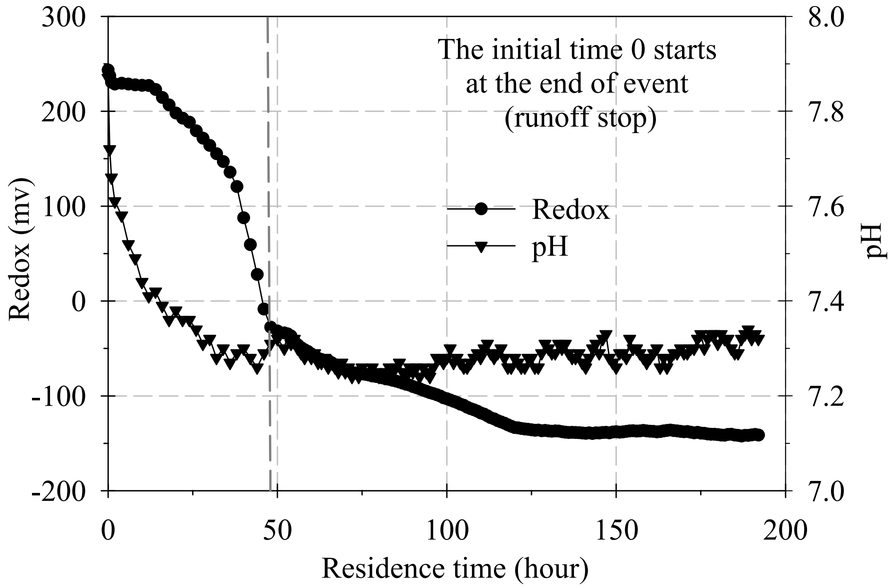


Figure 10. Time-dependent changes of redox potential and pH in rainfall-runoff detained after a treatment event.

Table 1. Summary of scouring run results for HS with a 2400-µm screen aperture preloaded by SP gradation. It includes testing data for scouring at 50% and 100% sediment capacity of sump and 1-inch sediment depth in volute section for each 100% and 125% of design operating flow. HS design flow rate = 493.7-gpm.

Flow rate [gpm]	Flow rate [%]	Sediment preload in sump [%]	Sediment preload in volute [inch]	Test duration [min]	Mean effluent conc. [mg/L]	Sediment scouring rate [g/min]
617.2	125	50%	No	12	117.4	267.9
493.7	100	50%	No	15	103.1	184.0
493.7	100	100%	No	15	174.9	300.7
617.2	125	100%	No	12	197.4	456.9
493.7	100	50%	1-inch	15	106.9	198.6
617.2	125	50%	1-inch	12	115.7	263.5
617.2	125	100%	1-inch	12	199.5	456.9
493.7	100	100%	1-inch	15	179.9	334.1